# Does Sub-millisecond Pulsar XTE J1739-285 Contain a Low Magnetic Neutron Star or Quark Star ?

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## ABSTRACT

With the possible detection of the fastest spinning nuclear-powered pulsar XTE J1739-285 of frequency 1122 Hz (0.8913 ms), it arouses us to constrain the mass and radius of its central compact object and to imply the stellar matter compositions: neutrons or quarks. Spun-up by the accreting materials to such a high rotating speed, the compact star should have either a small radius or short innermost stable circular orbit. By the empirical relation between the upper kHz quasi-periodic oscillation frequency and star spin frequency, a strong constraint on mass and radius is obtained as 1.51 solar masses and 10.9 km, which excludes most equations of states (EOSs) of normal neutrons and strongly hints the star promisingly to be a strange quark star. Furthermore, the star magnetic field is estimated to be about $4 \times 10^7(G) < B < 10^9(G)$, which reconciles with those of millisecond radio pulsars, revealing the clues of the evolution linkage of two types of astrophysical objects.

*Subject headings:* star: neutron — X-ray: stars — equation of state — pulsar: individual (XTE J1739-285 )

## 1. Introduction

The most rapidly spinning astrophysical object in the universe, named XTE J1739-285, rotating 1122 times per second, has been declaimed to be detected recently in the accreting X-ray binary system (Kaaret et al. 2007), which is the first sub-millisecond pulsar (spin period 0.89 ms) coming into our view since the discovery of the first radio pulsar by Jocelyn Bell and Anthony Hewish forty years ago (Hewish, Bell & Pilkingston et al. 1968) if the 1122 Hz is a spin frequency.

However it is stressed that the 1122 Hz burst oscillation frequency is detected in the only one burst but not the whole set of bursts (Kaaret et al. 2007), so this frequency still needs the further confirmation in the future burst detections. At the present time we take this 1122 Hz frequency as a tentative case, and based on this our investigations of its applications are processed. If the declared spin frequency 1122 Hz is fully confirmed, then this compact object breaks through the record of the fastest radio pulsar with the spinning frequency of 716 Hz (1.39 ms) discovered recently (Hessels et al. 2006). Strikingly, such a high spinning makes the edge velocity at the radius of 42.6 km the speed of light, which quantitatively constraints on the star size and its emission region. If this declaimed spin detection is true, it is interesting that such a high spinning does not break up the star, which provides us a unique opportunity to explore the matter compositions of the central object, neutrons or their constituent quarks that have been never seen as free particles to date. No doubt, such a high rotating frequency 1122 Hz should influence on the EOS of compact object and its mass-radius relation (Lavagetto et al. 2006; Bejger et al. 2006). In fact, the importance of detecting a sub-millisecond rotating pulsar as a way of discriminating the star nuclear compositions has been proposed by several authors (Phinney & Kulkarni 1994; Burderi & DAmico 1997; Burderi et al. 1999, 2001). The formation of a very fast spinning pulsar, however, depends sensitively on the history of the compact object in the binary and

on the evolution of its magnetic field (Possenti et al. 1998).

The source XTE J1739-285, exhibiting as a transient X-ray burst source, firstly discovered in 1999 by the satellite *Rossi X-ray Timing Explorer (RXTE)*, is recently reported that the burst oscillation frequency is detected at 1122 Hz (Kaaret et al. 2007), which is identified as a spin frequency because in the accretion-powered pulsar SAX J1808.4-3658 both a pulsation frequency and a burst frequency are detected at 401 Hz (Chakrabarty et al. 2003; van der Klis 2006; Yin, Zhang & Zhao, et al. 2007). The central object of XTE J1739-285 lies in a low mass X-ray binary (LMXB) and is believed to be a dense star with the incredible density, like what a solar mass is trapped into a area of 10 km as a result of the supernova explosion of some massive star. The magnetic field of this type of object is about $\sim 10^{8-9}$ Gauss, which experiences deduction from the original value $\sim 10^{12}$ Gauss by sucking the accreting materials from the disk fed by its companion (e.g. Bhattacharya & van den Heuvel 1991). The rotating of such a magnetic object will be responsible for its pulsation.

Measured mass and radius of compact object can be used to study the strong nuclear force of matter or the relation between the matter pressure and density, i.e. equation of state (EOS) (Lattimer & Prakash 2001, 2004, 2006; Glendenning 2000). Understanding the behavior of matter at the super-high density has a special priority in astrophysics because such an extreme condition cannot be imagined in the laboratory on Earth. The soft (stiff) EOSs predict lower (higher) pressures for same density, and most of these EOSs give the upper limit of star mass to be about 1.6 $M_\odot$. If a more massive mass is inferred, for instance the star mass M $\sim 2.1$ $M_\odot$ in EXO 0748-676 , then the soft EOS is ruled out (Özel 2006). **Three decades ago, the possibility of quark star was proposed and studied by Itoh (1970), Chapline & Nauenberg (1977) and Witten (1984).** Later on, the masses of quark stars have been calculated to primarily reconcile the mass

ranges of soft EOSs of NSs, but combined with the smaller radii (e.g. Lattimer & Prakash 2001, 2004, 2006; Dey et al. 1998; Haensel et al. 1986; Alcock et al. 1986). Combined with star mass-radius relation and other properties, the possible candidates of quark stars have been investigated, such as the X-ray source RX J1856.5-3754 (Drake et al. 2002), accretion-powered X-ray pulsar SAX J1808.4-3658 (Li et al. 1999), the X-ray burst sources GRO J1744-28 (Cheng et al. 1998) and 4U 1820-30 (Bombaci 1997), as well as the $\gamma$-ray bursters (Haensel et al. 1991). Moreover, the frequency distribution of X-ray neutron stars may reveal that a quark phase transition resulting from the changing central density induced by the changing spin (Glendenning & Weber 2001). From the inferred small 'apparent radius', one concludes the star inside 1E 1207.4-5209 may be composed of the strange quark matters (e.g. Xu 2005); the emission properties of strange quark star has been explored recently by Melrose et al. (2006). However, as pointed out, the astrophysical observations could not unambiguously distinguish the quark stars from normal neutron stars (Lattimer & Prakash 2004, 2006; Page & Reddy 2006; Watts & Reddy 2007).

The neutron star (NS) mass can be measured with high accuracy in the binary radio pulsar system (e.g. Kaspi, Taylor & Ryba 1994), for instance, the masses of double pulsar PSR J0737-3039 M=1.337(5) M$_\odot$ and M=1.250(5) M$_\odot$ (Lyne et al. 2004). Until now, around fifty NS masses have been measured with the averaged value of $\sim$1.4 M$_\odot$(Lattimer & Prakash 2004, 2006), from the possible minimum mass 0.97±0.24 M$_\odot$(Jonker et al. 2003) to maximum value 2.1±0.2 M$_\odot$(Nice et al. 2005). Unlike the situation of NS mass measure, there is no effective way of acquiring an accurate NS radius directly, thus the star EOS can be only estimated by some measures with errors (Zhang et al. 2007). Then some $M - R$ relations can be measured to derive $M$ and $R$ constraints (Özel 2006; Miller 2002), for instance, the "apparent radius" estimated from the thermal emission of perfect blackbody (Truemper et al. 2004; Burwitz et al. 2003; Rutledge et al. 2001; Burwitz et al. 2001; Haensel 2001), the gravitational redshift of the spectral lines (Cottam et al. 2004), and the

star magnetosphere limit of SAX J1808.4−3658(Burderi & King 1998), etc. As declaimed, it is important to confine the challenging attempts to measure the NS radius to the most reliable data and methods, otherwise we will continue to produce the radius values with the uncertainty of a factor of two or so, which is not enough to constrain EOS of NS matter (Truemper 2007).

## 2. Mass and radius estimation of XTE J1739-285

### 2.1. Constraints on mass and radius by the spin frequency

Located about 35,000 light-years away from Earth, the burst source XTE J1739-285 lies in an accreting binary system, where the orbital materials in the star inner disk of radius $r$ process the circle motion with Keplerian frequency $\nu_K$ (van der Klis 2006; Stella & Vietri 1999; Miller et al. 1998),

$$\nu_K = \sqrt{\frac{GM}{4\pi^2 r^3}} = 1833 \text{ (Hz)}(\frac{M}{\text{M}_\odot})^{1/2}(\frac{R}{10\text{km}})^{-3/2}, \tag{1}$$

which should be bigger than the spin frequency $\nu_s$ because the star in LMXB is experiencing the spin-up phase (e.g. van der Klis 2006) .

The Keplerian motion will end at the innermost stable circular orbit (ISCO) if the star surface is inside ISCO, so the spin-up process will be invalid there. The formation of the spin frequency of star in LMXB is due to the spin up of the accreted matter in the Keplerian motion, thus the Keplerian orbital frequency in the inner magnetosphere-disk boundary must exceed over the spin frequency (e.g. Bhattacharya & van den Heuvel 1991; Cheng & Zhang 2000; Lamb & Boutloukos 2007). Therefore, it is usually believed that the maximum Keplerian frequency occurs at ISCO with the radius $R_{\text{ISCO}} = 6GM$ (e.g. Miller et al. 1998; Zhang et al. 1998; see the illustration diagram Fig. 1), or ISCO lies inside the corotation radius $R_{co}$ at where the Keplerian frequency equals the star rotation spin

frequency, i.e. $R_{\rm ISCO} \leq R_{co}$,

$$\frac{R_{co}}{10\text{km}} = (\frac{M}{M_\odot})^{1/3}(\frac{1833}{\nu_s})^{2/3} \ . \tag{2}$$

Thus one has a mass constraint in the following (Miller et al. 1998)

$$\frac{M}{M_\odot} \leq \frac{2200(\text{Hz})}{\nu_s} \ . \tag{3}$$

As declaimed, for the given star mass and radius, the permitted maximum spin frequency is as follows (Lattimer & Prakash 2004, 2006)

$$\nu_s \leq 1045 \ (\text{Hz})(\frac{M}{M_\odot})^{1/2}(\frac{R}{10\text{km}})^{-3/2} \ . \tag{4}$$

Therefore, from Eq.(3) and Eq.(4) the mass-radius constraints can be obtained, which are plotted in Fig. 2.

For comparisons, several EOS curves are plotted in Fig. 2 as well. In the shadowed area of Fig. 2 with $M < 1.96 M_\odot$ and $R < 11.9 \ km$, where the meanings of its boundaries are indicated in the figure caption, we find that the too stiff EOSs are strongly excluded.

## 2.2. More stringent constraints on M and R by the kHz QPOs

However, if the higher twin kHz QPOs are detected in XTE J1739-285 , as derived from the other twin kHz QPO sources, we could even give a stronger constraint on the star mass upper limit. In theory, the Keplerian frequency of orbital matter, to which the upper kHz QPO frequency is identified, should be greater than the spin frequency because of the spinning up of star by accretion (Shapiro & Teukolsky 1983). From RXTE detections, the twin kHz QPOs, the upper and lower frequencies, are often found in the Fourier power spectra (van der Klis 2006), and it is also noticed that, for the known nuclear-powered millisecond pulsars with the simultaneously detected twin kHz QPO frequencies shown
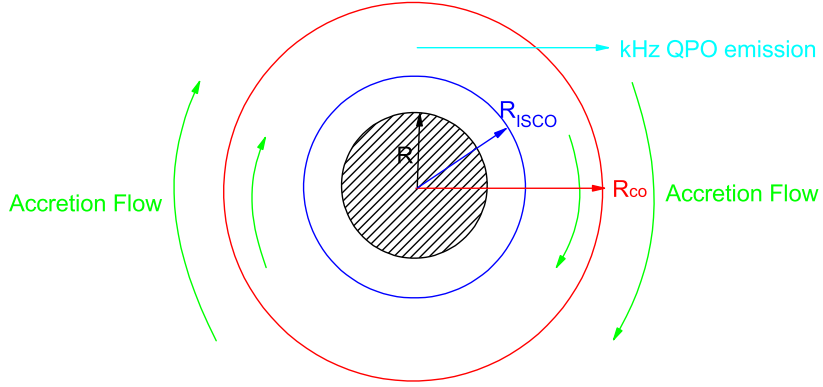
Fig. 1.— Illustrative diagram of ISCO and corotation radius, where the star surface inside the ISCO is assumed. The ISCO radius $R_{\mathrm{ISCO}}$ is three Schwarzschild radii ( $R_{\mathrm{ISCO}} = 6GM$), and the corotation radius $R_{co}$ is determined by the condition that the Keplerian frequency equals spin frequency at $R_{co}$ as described in Eq. (2), i.e. $\nu_K(R_{co}) = \nu_s$. ISCO is the innermost stable circular orbit, so the disk Keplerian flow should occur outside ISCO, implying the kHz QPO frequency and spin frequency to be less than the frequency at ISCO. The compact star in LMXB is experiencing the spin-up by the accreting matter, so the magnetosphere-disk boundary should be inside the corotation radius but outside ISCO.
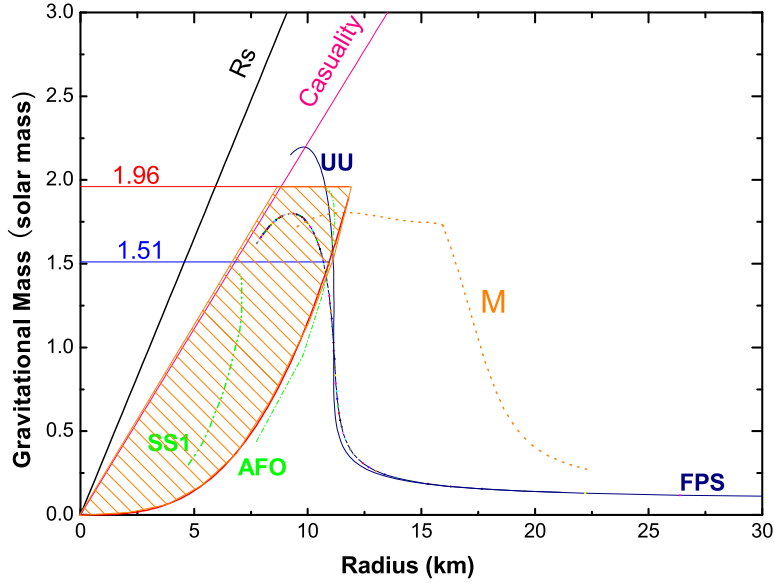
Fig. 2.— Mass-radius diagram of XTE J1739-285 . Five representative EOSs are shown (for their definitions, see Lattimer & Prakash 2001; Cook et al. 1994): stars containing quark matter (green color curves labeled SS1 and AFO), stars made of normal neutron matter (navy color curves labeled UU and FPS), and star with the pion condensation transition (orange color curve labeled M). The straight lines represent the constraints by general relativity and causality conditions, i.e. $R = 2GM$ and $R = 2.9GM$, respectively (Lattimer & Prakash 2004; 2006); the parabola curve represents the rotational constraint, as described in Eq.(4). The horizontal lines M=1.96 $M_\odot$ and M=1.51 $M_\odot$ are explained in the text. The shadowed area stands for the possible $M - R$ range of XTE J1739-285 , which covers the EOSs of the quark matter and normal neutron ($M < 1.96 M_\odot$), or EOS of the quark matter ($M < 1.51 M_\odot$).

in Table 1, their upper kHz QPO frequencies, usually identified as the Keplerian orbital frequency (van der Klis 2006; Stella & Vietri 1999; Miller et al. 1998), are all at least 1.3 times bigger than their spin frequencies (see Table 1; Yin, Zhang & Zhao et al. 2007), which implies the inner orbital accreting matter to enter into the region enclosed by the corotation radius. If this empirical relation is also valid for XTE J1739-285 though no twin kHz QPOs have been simultaneously detected in this source (Kaaret et al. 2007), one can conclude that the minimum upper frequency of twin kHz QPOs of XTE J1739-285 is bigger than about 1459 (=1.3×1122) Hz. Henceforth, the upper limit of mass constraint by Eq.(3) is changed to be M=1.51M$_\odot$. Interestingly, in the shadowed area of Fig. 2 with $M < 1.51$M$_\odot$ and $R < 10.9$ $km$, almost all plotted EOSs of normal neutrons and pion condensation transition are excluded, and only the model SS1 for quark matter (Dey et al. 1998) is possible. Accordingly, the compact object in XTE J1739-285 is more probably composed of quark matter, if the declaimed higher kHz QPO frequency is detected. Perspectively, these results sheds light on the study of sub-nuclear physics. In addition, it would be meaningful to detect the higher kHz QPOs than 1500 Hz in XTE J1739-285 , revealing a smaller mass value than 1.47 M$_\odot$inferred from Eq.(3), which will indispensably exclude EOSs of normal neutron matters. Furthermore, the $M - R$ constraints would be considerably improved if the star mass or some $M - R$ relations, e.g. the gravitational redshift and thermal emission, were known. In any case, XTE J1739-285 is a dramatically particular probe of exotic matter in extreme environments that cannot be achieved on Earth. While, as a conclusion, the sub-millisecond pulsar will definitely exclude the too stiff EOSs, implying that the star matter is highly incompressible or the big stars cannot endure too fast spin frequencies without breaking apart.

## 3.    On the magnetic field constraints of XTE J1739-285

The magnetic field of NS in the binary system can be measured directly by the cyclotron lines in the magnitude order of $\sim 10^{12}$ Gauss (Truemper et al. 1978), however the radio pulsars and low magnetic NSs in low mass X-ray binaries (LMXBs) have no such priorities. The magnetic field strength of radio pulsar is estimated by the assumption of magnetic dipole radiation accounting for its spin down, so the approximation is aroused by exploiting the presumed star parameters, i.e. M=1.4 $M_\odot$ and R=15 km (e.g. Manchester & Taylor 1977). As for the estimation of star magnetic field strength $B$ in LMXB, it is derived by the definition of magnetosphere radius, which is also inaccurate because of the unknown star mass and radius (e.g. Shapiro & Teukolsky 1983; Burderi et al. 1996). While, the situation will be improved if one can infer the star mass and radius of XTE J1739-285 . In the accreting binary system, the magnetosphere radius $R_M$ is about an half Alfvén radius and can be conveniently written as (Shapiro & Teukolsky 1983), $R_M = 0.43 \times 10^6 (cm)(\frac{B}{10^8 G})^{4/7}(\frac{\dot{M}}{10^{18}g/s})^{-2/7}(\frac{M}{M_\odot})^{-1/7}(\frac{R}{10\text{km}})^{12/7}$, or equivalently

$$B = (\frac{R_M}{R})^{7/4} B_f ,\tag{5}$$

$$B_f = 4.4 \times 10^8 \ (G) \ (\frac{\dot{M}}{10^{18}g/s})^{1/2}(\frac{M}{M_\odot})^{1/4}(\frac{R}{10\text{km}})^{-5/4} ,\tag{6}$$

where $\dot{M}$ is the accretion rate and $B_f$ is a field strength when $R_M = R$ ($B_f$ is named as a bottom field, see, e.g. Zhang & Kojima 2006; Burderi et al. 1996). With the inequality $R < R_M < R_{co}$, we obtain the magnetic field constraint as follows,

$$B_f < B < (\frac{R_{co}}{R})^{7/4} B_f .\tag{7}$$

For XTE J1739-285 , by means of the approximated conditions $2.9GM < R < 11.9 \ km$, $M < 1.96 M_\odot$ and Eq.(4) where the radius 2.9 GM is given by the casuality condition of general relativity (Lattimer & Prakash 2004, 2006), we obtain the lower and upper limits of

magnetic field of XTE J1739-285 as,

$$B > 4.2 \times 10^8(G)(\frac{\dot{M}}{10^{18}g/s})^{1/2} \ , \tag{8}$$

and

$$B < 9.97 \times 10^9(G)(\frac{M}{M_\odot})^{-13/6}(\frac{\dot{M}}{10^{18}g/s})^{1/2} \ . \tag{9}$$

XTE J1739-285 is identified as a less luminous Atoll source (Kaaret et al. 2007), so its long-term accretion rate should be as low as those of the usual Atoll sources, i.e. $\dot{M} \sim 10^{16}g/s$ (on the definition of Atoll source, see Hasinger & van der Klis 1986). In addition, if the star mass of XTE J1739-285 is set to be about $\sim 1M_\odot$, then its lower and upper limits of magnetic field strength are approximately given, $4 \times 10^7(G) < B < 10^9(G)$, which is compatible with the approximately derived field strength $\sim 10^8$ Gauss of millisecond radio pulsar (Bhattachaya & van den Heuvel 1991; van den Heuvel & Bitzaraki 1995). Therefore, the similar magnetic fields and spin frequencies of both the compact objects in LMXBs and millisecond pulsars in the binary systems strongly hint their relevant evolutionary linkage (van den Heuvel 2004). However, the magnetic field as low as $\sim 4 \times 10^7$ Gauss has not yet been discovered. In the accreting binary system, it has long been believed that NS spin is accelerated by the accretion (Alpar et al. 1982; Radhakrishnan, & Srinivasan 1982) and its field decays (Bhattachaya & van den Heuvel 1991; van den Heuvel & Bitzaraki 1995). The spin and magnetic field of XTE J1739-285 strongly reveals the evidence that the compact object in LMXB is the progenitor of millisecond radio pulsar, which strengthens our understanding on the formation and evolution of such a striking spinning object. On the other hand, the evolutionary linkage also means that some millisecond pulsars are involved in the quark matters inside stars. Apparently, to confirm the spin frequency and detect the higher kHz QPO frequency of XTE J1739-285 have the preferential importance to set the stringent limit on the physical parameter of its compact object.

Table 1.  List of the low-mass X-ray binaries with the simultaneously detected twin kHz QPO and spin frequencies.

| Sources[1] | $\nu_2$(Hz)[2] | $\nu_s$(Hz)[3] | $\nu_{2min}/\nu_s$[4] | Refs. |
|---|---|---|---|---|
| 4U 1608-52 | 802-1099 | 619 | 1.3 | [1] |
| 4U 1636-53 | 971-1192 | 581 | 1.7 | [2] |
| 4U 1702-43 | 1055 | 330 | 3.2 | [3] |
| 4U 1728-34 | 582-1183 | 363 | 1.6 | [4] |
| KS 1731-260 | 1169 | 524 | 2.2 | [5] |
| 4U 1915-05 | 514-1055 | 270 | 1.9 | [6] |
| XTE J1807-294 | 353-587 | 191 | 1.8 | [7] |
| SAX J1808.4-3658 | 694 | 401 | 1.7 | [8] |

[1]: On the QPO data, see Belloni et al. 2005, van der Klis (2006) and Zhang et al. 2006, the original references therein; [2]: upper kHz QPO frequency; [3]: On the spin frequency, see also Chakrabarty 2004; Strohmayer & Bildsten 2006; van der Klis 2006; Lamb & Boutloukos 2007; Yin, Zhang & Zhao, et al. 2007, the original references therein; [4]: the ratio between the minimum upper kHz QPO frequency and spin frequency. [1]: Hartman et al. 2003; [2]: Wijnands et al. 1997; [3]: Markwardt et al. 1999; 4: Strohmayer et al. 1996; [5]: Smith et al. 1997; [6]: Galloway et al. 2001; [7]: Markwardt et al. 2003; [8]: Wijnands & van der Klis 1998.

## 4. Consequences and Discussions

In the paper, we take the burst oscillation frequency of 1122 Hz of XTE J1739-285 to be the NS spin rate, however it still needs the further confirmation (e.g. Galloway 2007). At first, it is detected in the brightest burst with the significant at the 99.96% confidence level, not in a whole set of six bursts (Kaaret et al. 2007). Secondly, from a statistical point of view, the frequency of 1122 Hz is too far apart from the arrange of the previously known spin frequencies of LMXBs, from the minimum value of 45 Hz (Villarreal & Strohmayer 2004) to maximum 619 Hz (Hartman et al. 2003), centered at $\sim 400$ Hz (Yin, Zhang & Zhao et al. 2007), and it is much higher than the fastest spin frequency of radio pulsar 716 Hz (Hessels, Ransom & Stairs, et al. 2006). Therefore, we take this spin frequency of 1122 Hz as a tentative detection, or it might be considered that the signal of 1122 Hz is merely a candidate burst oscillation (e.g. Galloway 2007). In addition, we emphasize that this spin frequency is not yet verified totally and the present observation is not statistically as sound as for those of other LMXB's (see, e.g., Strohmayer & Markwardt 2002 for 4U 1636- 536; Strohmayer, Markwardt & Swank et al. 2003 for XTE J1814-338).

By means of this assumed highest spin frequency, we can constrain on the NS mass and radius, which indicates the frequency of 1122 Hz to be close to the centrifugal breakup limit for some equations of state of nuclear matter (e.g. Burgio, Schulze & Weber 2003). Furthermore, if the empirical relation on the kHz QPO frequency and spin frequency is presumed to be possible (see Table 1), then we can infer the higher kHz QPO frequency than 1500 Hz, which will exclude the EOSs of normal neutrons and just leave those of the strange quark matters possible. Therefore, the motivations for the physical properties of the super dense nuclear matters are enhanced (e.g. Page & Reddy 2006; Watts & Reddy 2007).

With the known spin frequency, combined with the constrained NS mass and radius,

the corotation radius of NS in XTE J1739-285  is inferred, by which the constraints of NS magnetic field strength is derived with the observationally estimated mass accretion rate. The similar estimation of NS magnetic field has been obtained for SAX J1808.4-3658 (Wijnands & van der Klis 1998), where the NS mass and radius are assumed, however in this paper we exploit the constrained mass and radius of NS to derive the ranges of NS magnetic field of XTE J1739-285 , which presents the upper and lower limits of magnetic field.

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